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Linking Landscape and Water Quality in the Mississippi River Basin for 200 Years

R. EUGENE TURNER AND NANCY N. RABALAIS

Two centuries of land use in the Mississippi River watershed are reflected in the water quality of its streams and in the continental shelf ecosystem receiving its discharge. The most recent influence on nutrient loading—intense and widespread farming and especially fertilizer use—has had a more significant effect on water quality than has land drainage or the conversion of native vegetation to cropland and grazing pastures. The 200-year record of nutrient loading to offshore water is reflected in the paleoreconstructed record of plankton in dated sediments. This record illustrates that the development of fair, sustained management of inland ecosystems is linked to the management of offshore systems. Land use in this fully occupied watershed is under the strong influence of national policies affecting all aspects of the human ecosphere. These policies can be modified for better or worse, but water quality will probably change only gradually because of the strong buffering capacity of the soil ecosystem.

Keywords: Mississippi River, water quality, agriculture, sustainability, environmental history

The local linkages between land use and water quality have cumulative effects within a region, its watershed, and the receiving coastal waters. The effects of these linkages vary as the cultural and ecological landscape varies with population growth, changes in land use, and climatic events. These changes have been particularly evident in North America over the past four centuries, as European culture was inserted into the North American continent, as the Native American Indians died from newly introduced diseases and were subdued through military and political means, and as the mostly European population grew and became urbanized. A high-intensity agricultural–economic system has turned the American Midwest into what is now known as the nation's "breadbasket," where 65% of the land in the 14 states of the Mississippi River Basin (MRB; figure 1) is farmland and 25% is harvestable cropland.

As the landscape changed in response to these developments, so too did the Mississippi River. Its main channel has been shortened and dredged, its banks stabilized for navigation, and flood protection levees built, which extend continuously south of Vicksburg, Mississippi. These levees have isolated the alluvial soils from the main channel, promoting agriculture development on alluvial soils (Abernethy and Turner 1987). The volume of river water extracted and returned by industrial plants in Louisiana is now greater than that discharged into the Gulf of Mexico (EARI 1975).

Today's significant water quality problems in the MRB are related to these landscape and industrial developments. Forty-four percent of the surveyed rivers in 15 MRB states were "impaired" in 2000 (EPA 2002). Nitrate concentration in the Des Moines River is sometimes greater than 10 milligrams per liter, which is the statutory maximum limit for drinkable water supplies (Hallberg 1987), and there were 1557 fish consumption advisories in the MRB in September 1996 alone (EPA 1998). Water-quality changes in the lower Mississippi River in this century can be linked in a plausible cause-and-effect relationship to the formation of a 20,000-square-kilometer (km^2) low-oxygen zone in coastal waters (Rabalais et al. 2002). The food web in this zone is poised to change from a productive food web of diatoms, zooplankton, and fish—which supports 25% of US fish landings—to one with diminished pelagic and demersal fisheries (Turner et al. 1998).

In this article we discuss two centuries of landscape changes that affect water quality in the MRB and in continental shelf

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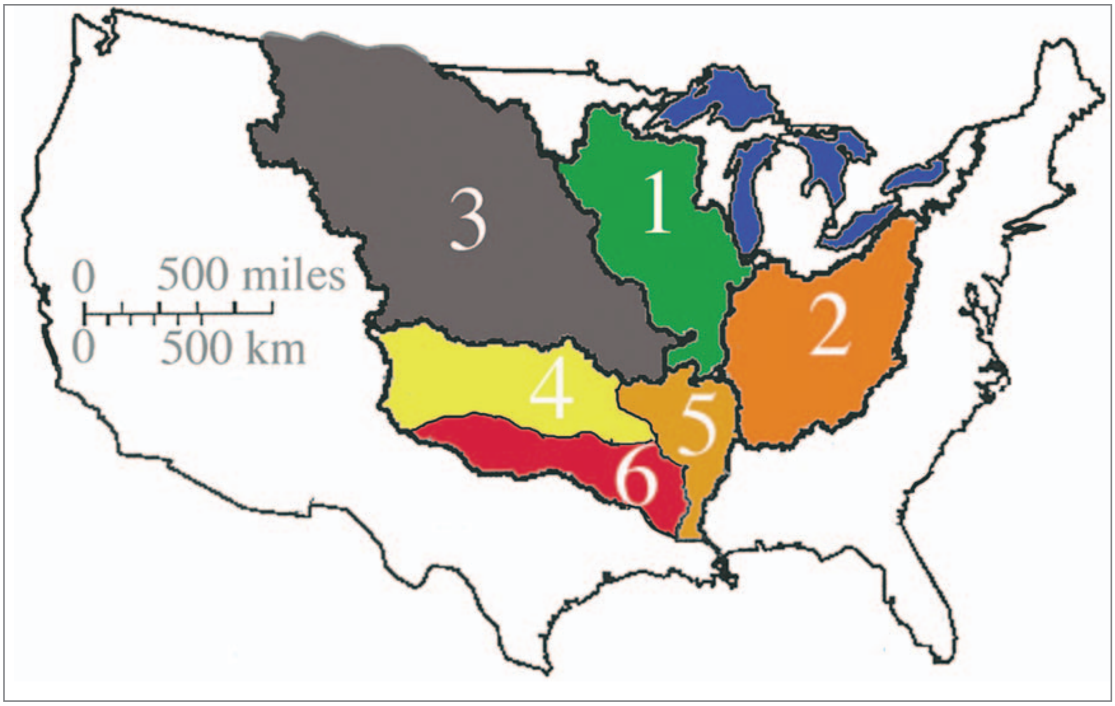

Figure 1. The Mississippi River Basin and the major watersheds discussed in this article. Key: 1, upper Mississippi River; 2, Ohio River; 3, Missouri River; 4, Arkansas River; 5, lower Mississippi River; 6, Red River. The total combined area is 41% of the contiguous states.

ecosystems. First, we reconstruct the timing of population growth and soil disturbance resulting from deforestation, cultivation, and drainage. Next, we draw connections between the subsequently higher sediment yields and the loss of nutrients from the newly disturbed landscape. To support the conclusion that the release of nutrients stored in the pre-European period was large, we cite experiments on small watersheds in which variables can be controlled, as well as anecdotal accounts from before the 1930s. Various analyses of the variability in water quality among watersheds support the conclusion that land use and population density are directly related to higher nitrogen yields and that these yields change important nutrient ratios. A paleoreconstruction of continental shelf sediments confirms the significance of these water quality changes to coastal food webs and suggests that the most recent influence on nutrient loading—intense and widespread farming—has affected water quality more than all previous landscape changes have.

Soil disturbance leading to soil loss

The sediment yield of a watershed is, in general, inversely related to the amount of vegetation present and to the accumulation of soil organic matter. The vegetation cover in the MRB was reduced as populations expanded during the 1800s. The population density of Native American Indians in the early 1600s was relatively low (no more than 106,000, or less than 0.1 person per km^2; Ubelaker 1992), in part because of diseases introduced by the Europeans. Population growth in the midwestern states began earlier than in the Missouri basin, reaching 1 to 10 people per km^2 by the 1850s (figure 2a), when the population center of the United States crossed the Appalachian Mountains and headed into the MRB in a west–southwest trajectory.

The area of land brought under cultivation rose with population growth (figure 2b). Cultivation was preceded by tree cutting, often by girdling the trunk, or burning. Trees were not routinely sold, so we inferred changes in forest area from the records of land use. Forest loss during the 1800s was quite rapid. The area of forest in Ohio, for example, went from 54% in 1853 to 18% in 1883 (Leue 1886). Greeley (1925) documented that the virgin forests of 1850 in the United States were largely remnants by 1920. Humphreys and Abbot (1876) estimated that 15% of the MRB was under cultivation or had "improvements" by 1860.

Did this agricultural expansion result in a significant increase in the sediment yield of the MRB? To find out, we assembled the suspended sediment records collected at the Carrollton water treatment plant in New Orleans (Louisiana) since 1903, when the existing unified treatment system was under construction. Additional data were reported by Quinn (1894), who sampled the Mississippi River for suspended sediments from 1879 to 1899. Data are also reported in Humphreys and Abbot (1876) for 96 weekly measurements from February 1851 to February 1853, for 7 additional measurements later in 1853, and for 36 data points for May through August 1846. These data (figure 2c) indicate that the suspended sediment concentration at New Orleans was highest in the late 1800s, when the area of new agricultural land brought into production each year was at its peak. Sediment concentration declined after 1910, especially after the period of extensive dam construction that began in the early 1950s on the Missouri River. Meade and colleagues (1990) documented that these dams trapped large amounts of sediments and dramatically altered the transport patterns of suspended sediments downstream in the basin all the way to New Orleans. Improved soil conservation practices may also have contributed to this decline (Trimble 1999).

Was there a long-term climate change in river discharge that caused these long-term variations in sediment yield? If discharge varies, then both the nutrient and sediment loads from a watershed are affected (load = concentration x discharge). Thus it is important to document the variability in water supply for the basin as a whole. A portion of the Mississippi River is diverted westward through control structures to join with the Red River to form the Atchafalaya River. This diversion, which was controlled in earnest after the record-setting 1927 flood, now constitutes about 30% of the main stem flow. The longest-kept discharge records are from upstream of this diversion at Vicksburg, Mississippi, the location of the US Army Corps of Engineers Waterways Experiment Station. These discharge records started in 1817, although some of the earlier records, which were based on empirical stage–discharge relationships calibrated without the benefit of today's technical conveniences, may be suspect. The discharge volume since 1817 varies around a long-term annual mean of 17,000 cubic meters per second (figure 3). The 170-year record of river discharge demonstrates no permanent rise or fall in the annual discharge volume. The influences of variable climate changes, therefore, are not considered an important cause of variations in sediment yields on the scale of decades.

The suspended sediment yield (mass per unit area) from the landscape certainly increased after European colonization of what was once an American Indian aboriginal province of hunter–gatherers with sparse and casual crop cultivation (Cronon 1983). The new colonists practiced row farming at an intensity previously unknown in these lands, and the switch to higher-intensity farming happened quickly. Row crop cultivation meant that existing vegetation was removed and the soil surface severely disrupted and compacted. Livestock roamed the woods for forage and further disrupted the soil surface. A visitor in the 1800s noted, "There is no portion of the globe that is being exhausted of its fertility by injudicious cultivation, so rapidly as the Mississippi Valley" (Bateham 1849, quoted in Whitney 1994, p. 226).

The effects of land use on soil erosion can be inferred from well-documented examples inside and outside the MRB. For example, Wolman (1967) discussed the changes in sediment yield from 1800 to 1960 for a

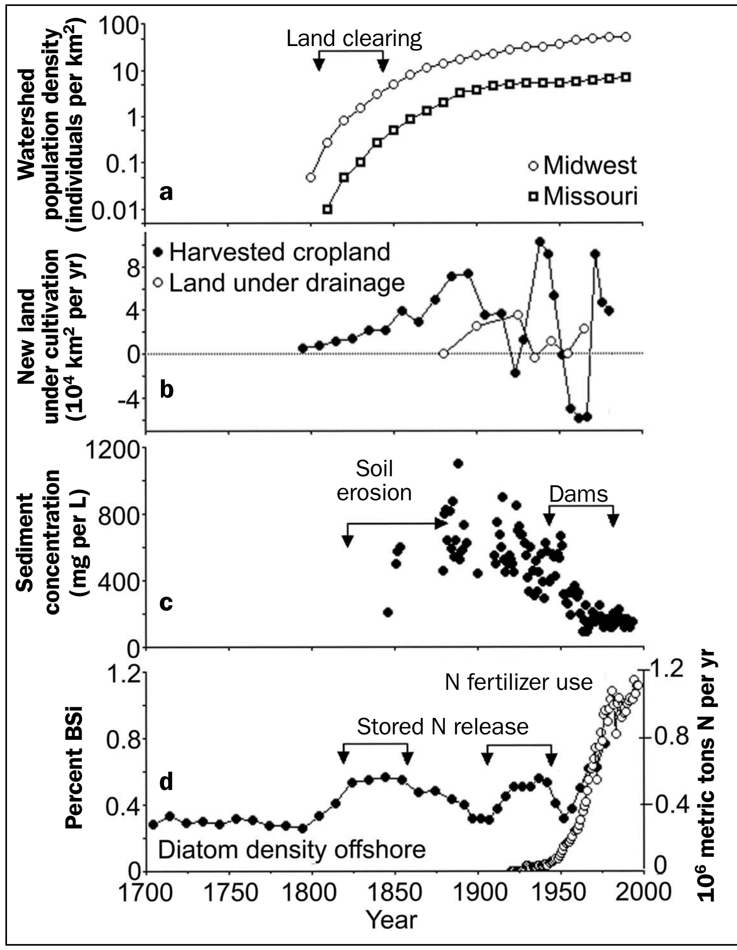

Figure 2. A summary interpretation of the relationships among population growth, land conversion to agriculture, and fertilizer use in the Mississippi River Basin (MRB) and coastal diatom production. (a) Population density in two regional groupings of states. The Midwest group consists of Ohio, Indiana, Illinois, Iowa, Michigan, Wisconsin, and Minnesota. The Missouri group consists of Montana, Wyoming, North Dakota, South Dakota, Nebraska, and Missouri. Population data are from the US Census Bureau and exclude Native Americans and slaves in most cases before 1850 (Anonymous 1992). (b) The new area of harvested cropland and land under drainage added each year in the MRB. Cropland data for before 1860 are from Humphreys and Abbot (1876), and subsequent census estimates are from the US Department of Agriculture (USDA). The rise in harvested cropland after a decade of decline is probably taking place on previously farmed land. The new land under drainage is from USDA census estimates (irregular intervals) (USCB 1961, 1973). (c) The annual average suspended sediment concentration (milligrams per liter) at New Orleans, Louisiana. Data are from the annual reports of the New Orleans Water and Sewerage Board, Quinn (1894), and Humphreys and Abbot (1876). (d) The percentage of biogenic silica (BSi) in sediments from dated sediment cores collected near the mouth of the Mississippi River (Turner and Rabalais 1994). Percentage BSi is an indicator of biogenic silica found in diatom remains (dry weight basis). Also included is the annual flux of nitrogen in the Mississippi River from 1920 to 1987.

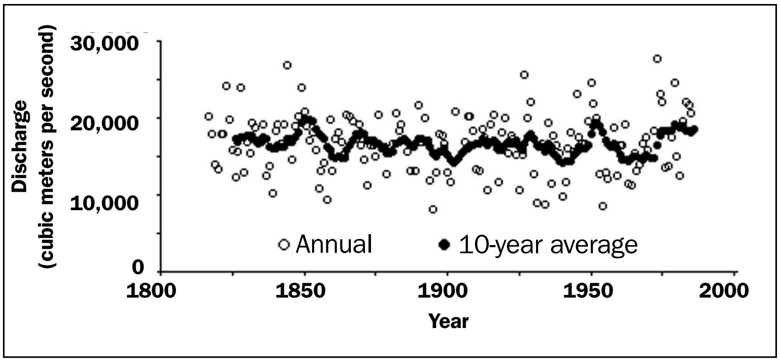

Figure 3. Mississippi River discharge at Vicksburg, Mississippi, for individual years and a 10-year moving average.

Maryland Piedmont stream: Erosion increased when the forest cover was removed for crops, declined when farms were abandoned, rose again with urban growth in the 1960s, and declined again as concrete and roads held soil in place while construction activities dropped off. In the MRB, Brune (1948) documented a 50-fold increase in sediment yield as cropland area increased (the amount of sediment was also affected by the drainage area). Brune also showed similar relations of sediment yield to drainage area and cropland for the Ohio River Basin. Meade and colleagues (1990) noted that conversion of forest to agricultural fields "caused orders-of-magnitude increases in soil erosion and corresponding increases in the sediment yields of rivers." In a letter to Jared Eliot in the mid-18th century, the naturalist John Bartram wrote,

> About 20 years past when the woods was not pastured and full of high weeds and the ground light(,) then the rain sunk much more into the earth and did not wash and tear up the surface (as now). The rivers and brooks in floods would be black with mud but now the rain runs most of it off on the surface (and) is colected [sic] into the hollows which it wears to the sand and clay which it bears away with the swift current down to brooks and rivers whose banks it overflows. (Cronon 1983, p. 147)

Trimble's provocative review of the history of soil management in the United States begins with these conclusions:

> Much of the American soil has been poorly treated since European settlement. Early travelers' accounts and a few systematic studies make this clear. Many early settlers brought poor agricultural practices with them: the Scots, for example, were known for their crude agriculture as late as 1780. On this continent, the cheap and unlimited land promoted a widespread attitude that land could be used, exhausted, or destroyed as the case may be, and then abandoned for new land. Such a system existed well into the twentieth century, at least in much of the southeast, and the depredations on the landscape are still visible today. (Trimble 1985, p. 162)

These effects of agricultural expansion on soil erosion (figure 4) were widely acknowledged by the 1930s as having major consequences for farm management. The amounts of soil loss under cultivation could be staggering and quick. A 1928 US Department of Agriculture publication on soil erosion described how "certain piedmont areas whose records are known have, within a period of 30 years, lost their topsoil entirely, 10 inches or more of loam and clay loam having washed off down to the clay subsoil" (Bennett and Chapline 1928). The authors of that report described how an apple orchard near Lookout Mountain in northeastern Kansas had the trunks of trees completely buried by overwash of silt from neighboring lands, so that the level of the ground was at the branches, and they described gullies that were 300 feet wide in places and three-quarters of a mile long (Bennett and Chapline 1928). They concluded that "it seems scarcely necessary to state the perfectly obvious fact that a very large part of this impoverishment and wastage has taken place since the clearing of the forests, the breaking of the prairie sod, and the overgrazing of pasture lands. A little is being done here and there to check this loss—an infinitesimal part of what should be done" (p. 23).

A 1935 Iowa State Planning Commission document (cited in Prince 1997) noted that disturbance of the state's prairie had caused the loss of 192,643 metric tons per km^2 of soil and that 40% of Iowa had lost 50% to 75% of its surface soil. Data for farmland at an Oklahoma agriculture experiment station showed that the water runoff from land cultivated continuously in cotton was 11 times greater, and the soil losses 760 times greater, than from the same kind of land covered with ungrazed Bermuda grass (6-year average, 1930–1935; USDA 1938). Soil losses from 1894 to 1935 for land continuously planted with corn at the Ohio Agricultural Experiment Station were 63% of the organic matter and 4.05 centimeters (cm) of soil; the losses for land planted with oats over the same period were 36% of organic matter and 2.64 cm of soil (USDA 1938). Such high sediment losses are not unusual. Erosion rates of 100, or even 1000, times higher after land clearing are common (Novotny 1999). Within the MRB, the sediment yields are highest with cultivation of row crops and lowest with dense plant cover. For example, the suspended sediment in runoff from modern-day forests (which are not mature forests) is one-third of that from land planted with corn and soybeans (table 1).

As a result of these massive changes, sediments, including soil organic matter, were washed off the land and into small creeks, rivers, and, at least to some extent, the coastal zone. Recognition of the seriousness of soil erosion led to the formation of the Soil Erosion Service (renamed the Soil Conservation Service in 1935, now the Natural Resources Conservation Service) and to the classic 1934 Reconnaissance Erosion Survey.

Although preimmigration suspended sediment yields in the MRB were not recorded, there are proxy measures. These proxy measures are in sediment cores from the Mississippi River Delta that have been dated and analyzed for indicators

Table 1. Suspended sediment, total phosphorus, and nitrate yields in runoff by dominant land use in the United States for 1980–1989.

	Runoff (kilograms per square kilometer per year)		
Land use	**Suspended sediment**	**Total phosphorus**	**Nitrate**
Wheat	3503	3.5	11.2
Urban	8056	41.7	192
Forest	10,858	22.1	89.3
Rangeland	11,559	6.0	10.9
Mixed crops	27,671	23.1	107
Corn and soybeans	35,026	57.1	326

Source: Smith et al. (1996).

of phytoplankton production (Turner and Rabalais 1994). Diatoms, in particular, leave a record of their abundance in the siliceous frustules deposited on the bottom. Quantifying these frustules in sediments yields a surrogate or proxy measurement of algal production in the surface waters. The accumulation of this biologically bound silica (BSi) showed a distinctive rise at the beginning of the 1800s (figure 2d). It later declined to a low around the 1900s, underwent another rise and fall, and then rose again over the last 30 to 40 years. The diatom production rate is thought to be limited by the supply of nitrogen, much as an agricultural crop is nutrient limited, but in a different physical setting. The annual BSi accumulation has risen in proportion to the documented loading of nitrogen in the river from 1950 to 1990 (Turner and Rabalais 1994). Is the source of the nitrogen that caused the rise in BSi offshore in the 1800s and early 1900s related to an increase in nutrient yields accompanying soil erosion from the MRB?

Nutrient release from soils

When soils are disturbed enough during cultivation, the ecological processes that keep nutrients bound up in the soil and organic matter are subdued, and the stored nitrogen is released until the soil is, as an agriculturist might say, "exhausted"—meaning that the natural fertility of the soil is diminished to the point that crop growth is compromised. This is the MRB equivalent of the slash-and-burn agriculture found in the tropics, a farming practice in which crops are planted amid a shifting mosaic of soils that are newly exploited, in decline, or abandoned to natural rehabilitation. The US presidents Washington and Jefferson wrote about soil exhaustion. Later, so did naturalist John Muir:

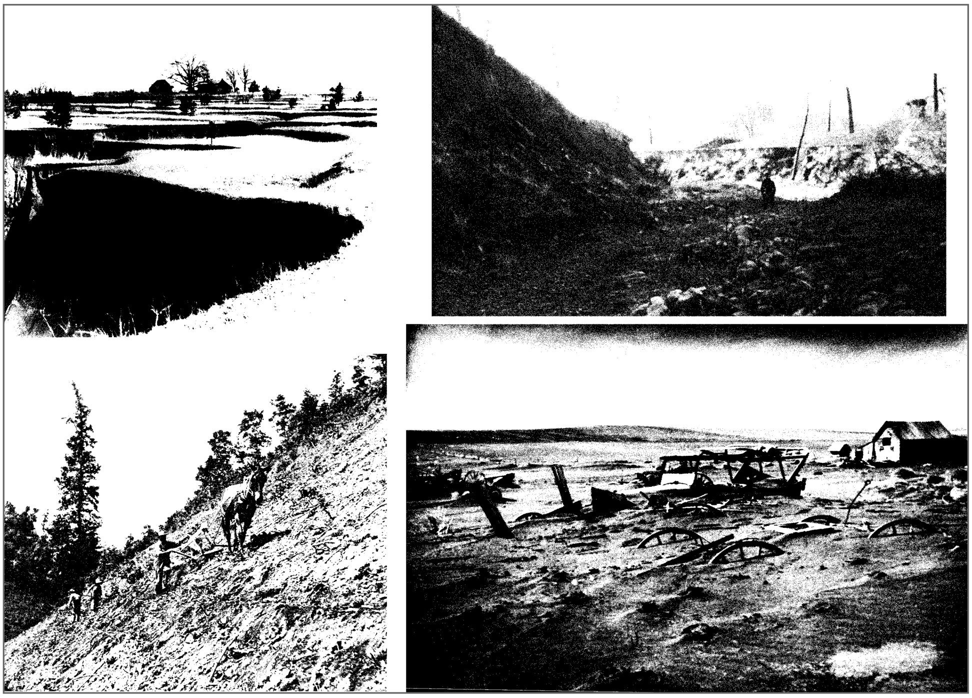

Figure 4. Photographs of the effects of soil erosion, 1910 to 1939. Top left: erosion in Chilton County, Alabama, circa 1935; cotton was grown on this field in 1910. Top right: line fence crossing a tributary in Winon County, Minnesota, in 1939. The posts and wire show the form of the stream and floodplain at the time the fence was rebuilt 5 years earlier; the photograph shows the channel trenching and widening since then. The man in the photograph is 6 feet tall. Bottom left: Two mules on a hillside plowing corn, circa 1935. Bottom right: buried machinery in a barn lot in Dallas, South Dakota, in 1936. Photographs: National Archives (NLR-PHOCO-53227 [600], WR 10 26, RG 083 G 36711, and 114 SC 5089).

> At first, wheat, corn, and potatoes were the principal crops we raised; wheat especially. But in four or five years the soil was so exhausted that only five or six bushels an acre, even in the better fields, were obtained, although when first plowed twenty and twenty-five were the ordinary yield. More attention was then paid to corn, but without fertilizers the corn crop also became very meagre. At last it was discovered that English clover would grow on even the exhausted fields, and that when plowed under and planted with corn, or even wheat, wonderful crops were raised. (Muir 1965, p. 164)

Gray's (1933) review of southern agriculture up to 1860 characterized soil exhaustion as an expected consequence of a way of farming: "Planters bought land as they might buy a wagon—with the expectation of wearing it out...[as the] wave of migration passed like a devastating scrooge [sic]. Especially in the rolling piedmont lands the planting of corn and cotton in hill and drill hastened erosion, leaving the hillsides gullied and bare" (p. 446).

Soil nitrogen is one of the exhausted nutrients, and the nitrate ion is particularly mobile. When a forest was clear-cut in Gale River, New Hampshire, the nitrogen losses went from an annual *retention* of 200 kilograms (kg) nitrogen as nitrate (nitrate-N) per km^2 as an undisturbed forest to a loss of 3800 and 5700 kg nitrate-N for the first and second years, respectively, after clear-cutting (Pierce et al. 1972). These loss rates are 10 to 20 times higher than the present total nitrogen (TN) yields for the whole MRB (489 kg TN per km^2 per year; Goolsby et al. 1999). To put these loss rates in perspective, consider that the present carbon, nitrogen, and phosphorus yields from the MRB are less than 0.1% of the carbon, nitrogen, and phosphorus in a layer of soil 1 meter thick with a 2% organic content. A small change in the element inventory on land can thus significantly change water quality in stream channels. These disturbances can have long-term consequences, too. Aber and colleagues (1998) studied the nitrogen dynamics of a northeastern forest and came to the conclusion that land-use history going back as far as 200 years had a stronger influence on nitrate losses than did modern-day nitrogen inventories or depositions.

The application of technological inventions in the 1800s introduced changes to farming practices. The wide-scale use of the iron plow, threshing machine, mower, and reaper began between 1825 and 1850. The first patent for a chemical fertilizer was issued in 1849 to the Chappell brothers in Baltimore, and subsequent phosphate fertilizer production centered around Charleston, South Carolina, in the late 1800s. The first agricultural journals appeared—*The American Farmer* (Baltimore, 1819), *The Plow Boy* (Albany, New York, 1819), *The New England Farmer* (Boston, 1822), *The New York Farmer* (New York, 1827), and *The Southern Agriculturist* (Charleston, 1828)— as land management practices evolved toward less land clearing and more intensive use. The newer approaches to soil management also led to high nutrient losses relative to the losses from continuously vegetated land. A 2-year study from one of the new agricultural experiment stations in the early 1900s documented that the conversion of the bluegrass native prairie vegetation to continuous wheat or corn, or to plowed fields, resulted in the loss of up to 160 times more nitrogen and 350 times more phosphorus than lost from the native landscape (figure 5).

Ditching and tile drainage further stimulated nitrogen losses from soils. Soil drainage is intended to dry out soils by promoting belowground drainage. The majority of dissolved nitrogen lost in a drained field is in the form of nitrate, and the nitrate is lost by movement as shallow, subsurface flow or as deeper groundwater, not as overland flow (Lowrance 1992).

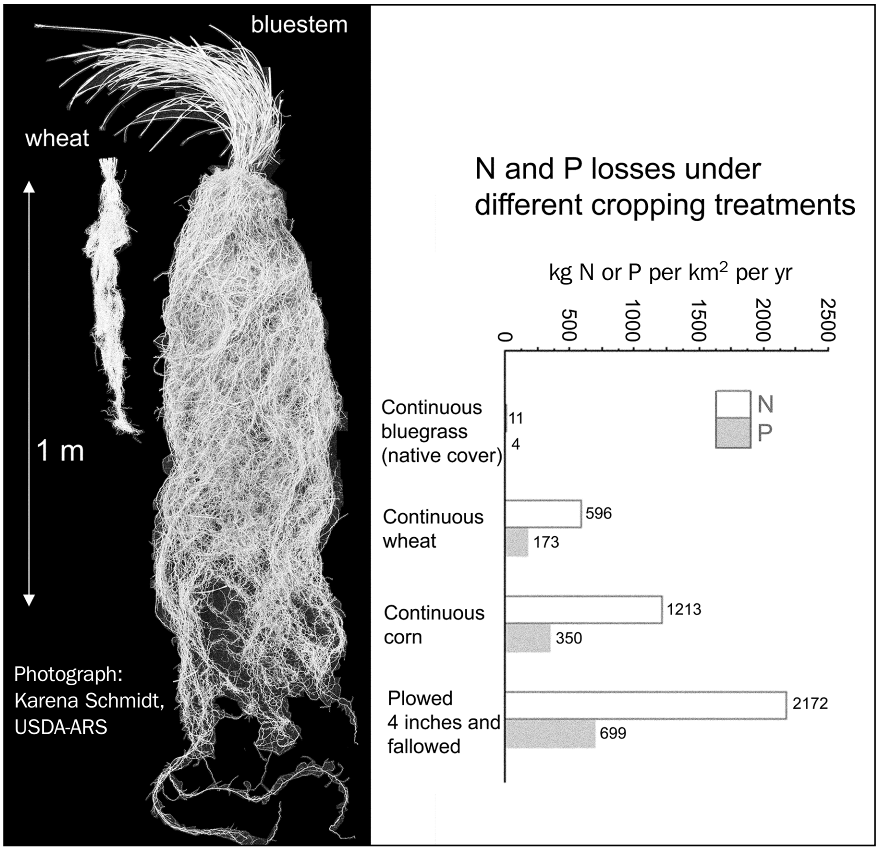

Figure 5. Average nitrogen (N) and phosphorus (P) losses (kilograms per square kilometer per year), 1 May 1926 to 1 May 1928, in runoff from experimental plots at the Missouri Agriculture Experiment Station (Miller and Krusekopf 1932). A belowground vertical profile of the roots in wheat* (Triticum aestivum) *and native big bluestem* (Andropogon gerardi) *prairie vegetation is shown.

Several studies have documented a strong and proportional relationship between nitrogen applications to surface soils and the nitrogen content in soil pore water and groundwater (Baker and Laflen 1983, Keeney 1986, Hallberg 1989). Nitrate accumulation in soil water of experimental plots in Virginia and Nebraska, for example, increased as nitrogen fertilizer application rates increased (Hahne et al. 1977, Schepers et al. 1991). Tile drainage promotes these leaching losses, reduces the amount of soil nitrogen, and increases nitrate in the groundwater, which eventually becomes surface water (Hallberg 1989).

John Johnston was the first person to lay drain tile in the United States, which he did on his farm in Ithaca, New York, in 1835 (USDA 1938). Drainage improved crop yields on marginal lands, but it took decades for the practice to spread to the Midwest (figure 2b), as marginal farmland came increasingly under cultivation after the passage of the Swamp Land Acts and the expansion of the railroads, which owned vast tracts of land. These drainage activities may not have been the only cause of greater losses of nitrogen in the soil, but they are indicative of the increased level of soil disturbance to the existing land and of expansion into formerly waterlogged soils.

The sequence of colonization, land clearing, agricultural expansion, soil erosion, increased nitrogen loading, and offshore diatom growth is summarized in figure 2. The BSi peaks and declines coincide with land-use changes resulting from land clearing, expansion of agriculture, and land drainage efforts within the MRB; they are modulated by the natural restoration of abandoned land. Note that the percentage of BSi in sediments accumulating offshore is higher now than it was during the peak in the mid-1800s. This recent rise in BSi concentration is undoubtedly related to increased nitrogen loading from the river, which occurred as a direct consequence of fertilizer application rising dramatically after World War II (figure 2d). Several analyses of whole watersheds have shown that the amount of fertilizer applied is sufficient to account for the postwar rise in nitrate in the Mississippi River (Peierls et al. 1991, Turner and Rabalais 1991, Howarth et al. 1996, Caraco and Cole 1999, Goolsby et al. 1999) and that urban and atmospheric nitrogen sources are relatively small (Howarth et al. 1996, Jordan and Weller 1996, Burkart and James 1999, Caraco and Cole 1999, Goolsby et al. 1999). However, the soil nitrogen pool is also significant, and it undoubtedly still contributes nitrate to the main channel of the Mississippi River.

Nutrient concentrations today

The effect of present land use on river water quality throughout the United States can be seen by examining the variability in water quality among watersheds. Jordan and colleagues (1997) showed that nitrate yields went up, and the ratios of dissolved silicate to nitrate went down, as the area of cropland increased in 27 watersheds of the Chesapeake Bay. Smart and colleagues (1985) studied watersheds in the Missouri Ozarks in the summer of 1979 and found that the silicate:nitrate ratio and the nitrogen content in water went up as the land in pasture increased (there were apparently few row crops in that area); they concluded that the stream nutrient concentrations were more strongly related to land use than to bedrock geology. They developed a statistical model that used watershed size and the percentage of urban land to describe 43% of the variation in total phosphorus yields among watersheds. Eighty percent of the variation in total nitrogen was described using the percentage of land in pasture and urban area. Perkins and colleagues (1998) showed similar results for all four major types of Missouri watersheds, as did Jones and colleagues (1976) for 34 watersheds in northwestern Iowa (3-year data set). One interesting pattern in Jones and colleagues' (1976) data set is that the nitrogen yield dropped rapidly with a small increase in the percentage of land as marsh, and it continued to fall to less than 1 kg per hectare

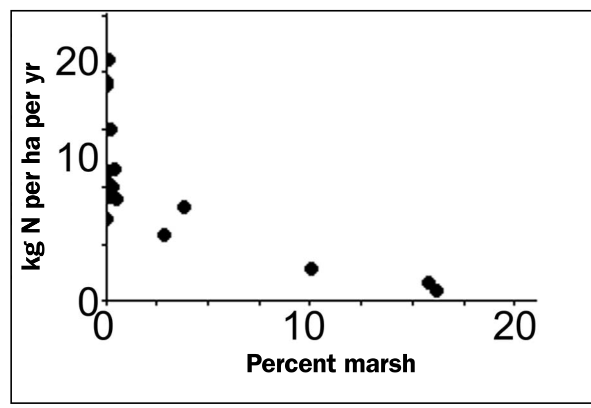

Figure 6. Relationship between the percentage of a watershed in Iowa that is marsh and nitrogen from nitrate and ammonium (kilograms per hectare per year) for 17 watersheds over 100 hectares, 1971 to 1973. Adapted from data in Jones and colleagues (1976).

(ha) when the watershed was 15% marsh (figure 6). This finding suggests that strategic restoration of wetlands throughout the upper watershed may be a useful approach to restoring water quality (Mitsch et al. 2001), especially where the nitrate concentration is high (Turner 2003a).

Many studies have concluded that the application of fertilizers is a major source of the increased nutrient loading among large river watersheds in the last 50 years (NRC 1993). The major contributor to these changes in the Mississippi River watershed is nitrate (figure 7). These observations substantiate the conclusion that human intervention within the natural landscape has transformed water quality on the scale of the world's largest river basins and smaller coastal watersheds (e.g., Turner and Rabalais 1991, Howarth et al. 1996, Jordan et al. 1997, Vitousek et al. 1997, Caraco and Cole 1999, Turner et al. 2000, 2003, Seitzinger et al. 2002).

Changes in nutrient ratios, and not just nutrient concentrations, also have important consequences for diatoms in the receiving coastal waters, which are generally limited by silica deficiency when the ratio of silicate to dissolved nitrogen drops below 1:1. Zooplankton graze on diatoms (which can be relatively large phytoplankton) and become part of the food web leading to fish production, among other things. The present-day concentrations of nitrate and silicate at New Orleans are very different from those in the early part of this century (figure 7), so much so that the atomic ratio of silicate to nitrate has fallen from about 4:1 to about 1:1. When the atomic ratio of silicate to nitrate falls below 1:1, the food web off the Mississippi River seems to switch from a diatom-based ecosystem to another ecosystem state that may be less desirable (Turner et al. 1998, Turner 2003b). The trends in many large rivers are in a similar direction (Turner et al. 2003). These changing nutrient ratios offshore of the Mississippi River affect an area from which 25% of the US commercial fisheries capture occurs. Many large rivers are changing in a similar way (Turner et al. 2003) and leading to eutrophication and hypoxia, which is having an unfavorable effect on the world's marine fisheries (Diaz and Rosenberg 1995). Thus, compromises to the quality and quantity of the diatoms in coastal waters could have unfavorable and significant consequences to food webs, commercial fisheries and recreational fishers, and coastal economies.

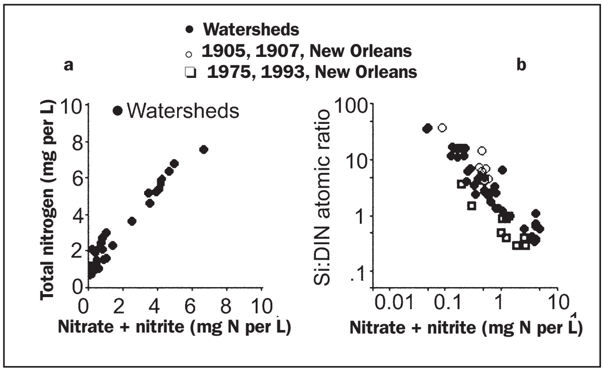

Figure 7. (a) Relationship between total nitrogen (y-axis) and combined concentration of nitrate and nitrite (x-axis) for 42 subwatersheds of the Mississippi River Basin (from data in Goolsby et al. 1999). (b) Relationship between the atomic ratio of dissolved silicon to dissolved inorganic nitrogen (y-axis) and the concentration of dissolved nitrate and nitrite (x-axis) for 42 subwatersheds of the Mississippi River Basin (from data in Goolsby et al. 1999) and for 529 individual sampling events at New Orleans.

The scale of water quality changes in the MRB over the last 200 years is substantial, and the social infrastructure supporting the humanmade landscape is nontrivial and important to many. This particular watershed has been anything but an equilibrium system for the last 200 years, suggesting that additional changes are forthcoming. Population growth alone will cause new changes in water quality. The landscape developments described herein have already resulted in nitrate levels in drinking water sources that exceed national standards. These developments have also contributed to the formation of the largest coastal low-oxygen zone in the western North Atlantic (Rabalais and Turner 2001, Rabalais et al. 2002) and to the eutrophication of inland and coastal waters, which is a widely acknowledged social and environmental concern (e.g., Nixon 1995). Concerns about flood protection for farmland and homes are intermingled with concerns about diminishing natural resource quality and quantity and with national political agendas involving international trade, global climate change, and food supplies. It is our challenge as scientists, citizens, land managers, and agriculturists, among others, to work toward a mutually satisfying equilibrium of interests that is sustainable, ethical, and socially responsive. Our view of soil and land management can be much broader than the articulated and commonly held view of a popular soil textbook of 40 years ago: "After all, our primary aim in soil management is to seek the highest yields we can maintain consistent with greatest profit" (Thompson 1957, p. 363). This view of "profit" could be enlarged to include off-farm social costs and benefits, the soil's health over decades, and the sustenance of the farming social structure, including the family-owned farm.

One thing seems certain: It took decades for the present system to develop, which suggests that it will take decades of working together for water quality rehabilitation to succeed. Three examples provide a perspective on just how patient we may have to be. First, the unfertilized fallow soil at the experimental soil plots in Rothamstead (United Kingdom) continues to leak significant amounts of nitrogen after 40 years (Addiscott 1988). A second example is from Sweden, where nitrate leaching from a grain field continued almost unabated 13 years after fertilizers were no longer added (Löfgren et al. 1999). Data on river water quality following the collapse of agriculture (circa 1990) in the former Soviet republics of Estonia, Latvia, and Lithuania show that, although fertilizer application fell to the level of the 1950s, the concentration of inorganic phosphate and nitrogen was the same in 1994 as in 1987 (Löfgren et al. 1999). The soil nitrogen mineralization of the huge soil nitrogen pool in these Baltic states is 50 to 200 kg nitrogen per ha compared with 64 to 93 kg nitrogen per ha of fertilizer applied. The strong buffering capacity of soils is becoming evident (Stålnacke et al. 1999). Understanding and managing the soil nutrient pools and turnover is a key factor in water quality management and will be inextricably commingled with the social structure and diverse incentives that have dominated soil cultivation practices for the last 200 years.

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